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PREDICTION OF THE CHARACTER OF TEMPERED GLASS FRACTURE

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The mechanism of tempered glass fracture is analyzed. Calculation methods are proposed for determining the degree of tempering required to ensure the safe character of glass fragmentation, the number of glass fragments resulting from fracture, and their average size.

The nature of fracture of tempered glass determines its degree of safety, The minimum number of fragments of tempered glass for a prescribed area of 5×5 cm^2 is limited by GOST 5727–88. It is known that the number of fragments is proportional to the degree of tempering of the glass, i.e., to the tensile stresses in the middle layer of the tempered glass. However, in spite of the fact that standards similar to the one quoted here exist in all industrial countries, the problem of the minimally required degree of tempering which ensures the safety of glass of different thickness or composition remains unanswered.

The reason for that is probably as follows. Although the problem of the interrelation between the degree of tempering and the number of the fragments resulting from fragmentation of a specific glass was first studied by P. Acloque in 1956 [1], that paper, as well as some later works, were based on the experimental investigations. Owing to the difference in the experimental methods used and the glass compositions investigated, the data obtained by J. Barsom, K. Akeioshi and E. Kanai, and V. Novotny [2 – 4] do not provide an answer to the question mentioned above.

In [5], the method for predicting the number of fragments makes it possible to account for the physical properties of different glass compositions (namely, the modulus of elasticity of the glass). However, the calculations were based on the Rittinger law of comminution (the law of surfaces). Therefore, the final formula contains the proportionality factor between the work done on fragmentation and the resulting surface (the Rittinger coefficient) found experimentally. In spite of the fact that the method in [5] is more universal with respect to the modulus of elasticity of a particular type of glass, it has the same limitations as the other four.

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The purpose of the present paper is to elucidate the interrelation between the degree of tempering of glass and the number of the fragments resulting from fracture, and to determine the minimum degree of tempering required to ensure the safe character of fragmentation of tempered glass.

In fracture of tempered glass, cracks propagate in its middle layer, which is in a state of strain [6]. Let us represent this layer as a separate plate, whose thickness for glass tempered industrially [7] is

$$h = \frac{1}{\sqrt{3}} \delta, \tag{1}$$

where δ is the thickness of the glass.

It would be correct to make the calculation relating the number of the fragments N to the stresses in the central (middle) layer σ_c in the case of uniform strain of the plate across the entire thickness h. However, in tempered glass the stresses across the plate thickness vary. Let us introduce the average stress value over the plate thickness [8] for industrially tempered glass

$$\sigma_m = \frac{2}{3} \sigma_c. \tag{2}$$

The fracture of tempered glass is the self-supporting fracture of a fragile body, and one can talk of the appearance of a fracture wave [9]. Consider a plate of thickness h that is situated in a uniform field of main tensile stresses σ_m. The stationary character of propagation of the fracture wave is possible only when its velocity is equal to the velocity of propagation of longitudinal elastic waves c_0 which can be determined by formula [10]

$$c_0 = \sqrt{E/\rho_0}, \tag{3}$$

where E is the modulus of elasticity of the material; ρ_0 is the density of the material before fracture.

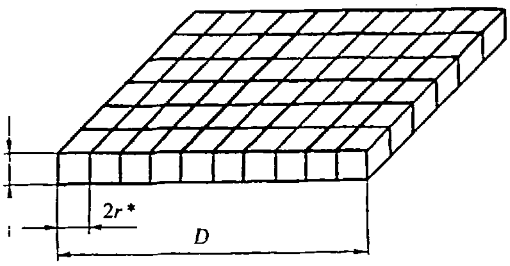

Fig. 1. Scheme of fragmentation of tempered glass.

The specific energy dissipation on the fracture front [10]

$$E_p = \frac{\sigma_m^2}{2E\rho_0}(1-2\nu), \tag{4}$$

where ν is the Poisson coefficient.

Knowing the quantity E_p, it is possible to calculate the geometrical dimensions of the fractured body particles. We will consider all particles as spherical since a spheroid shape of the particles is the best with respect to energy.

The surface energy of a spheroid particle with radius r is equal to

$$E_p = 4\pi\gamma r^2, \tag{5}$$

where γ is the density of the surface energy (for float-glass $\gamma = 2.1$ J/m^2),

The radius of the particle r can be determined by the formula in [10]

$$r = 3\gamma/\rho_0 E_p. \tag{6}$$

We assumed that the plate is fragmented into spheroid particles. However, experience shows that this type of fragmentation with the emergence of needle-shaped (scale-shaped) fragments is typical only of well-tempered glass (tempering degree $\Delta > 4$ pore/cm). At the same time, it has been proved theoretically [11] and confirmed experimentally [6] that the most probable shape of tempered glass fragments is a rectangular parallelepiped square in the plane.

Based on that, we assume that the glass pane is fractured precisely in this way. (Fig. 1). Therefore, the radius of the spheroid particle of the fractured material, taking into account expression (4), is

$$r = \frac{6E\gamma}{\sigma_m^2(1-2\nu)}. \tag{7}$$

The surface energy of the particle shaped like a rectangular parallelepiped with the half-length of the square base r is equal to

$$E_m^* = 8\gamma(r^2 + rh). \tag{8}$$

Since the surface energy of a particle of the fractured material is proportional to its typical size, the true meaning of the half-length of the parallelepiped base r^* can be found in the following way:

$$E_p^*/E_p = r^*/r.$$

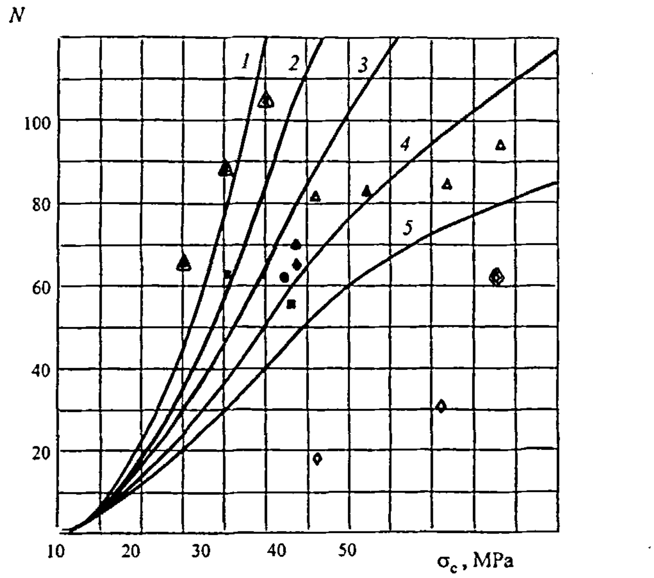

Fig. 2. Interrelation between stresses in the central layer σ_c and the number of fragments N resulting from fracture of glass: ———) calculation results ($E = 6.8 \times 10^{10}$ Pa, $\nu = 0.22$, $\gamma = 2.1$ J/m^2, $D = 0.05$ m); *1, 2, 3, 4,* and *5*) correspond to $\delta = 2, 3, 4, 5$, and 6 mm, respectively. ♦, ◊, ◇) data from [2] for $\delta = 4.8$, 5.6, and 9.5 mm, respectively; □, ■) data from [3] for $\delta = 3$ and 4.9 mm, respectively; ⧋, ▲, △) data from [4] for $\delta = 3.8$, 4.8, and 9.5 mm, respectively; ●) data from [5] for $\delta = 5$ mm.

Taking into account formulas (4), (7), and (8)

$$r^* = \frac{2}{\pi}(r + h).$$

Taking into account expressions (1) and (7), it can be written that the half-length of the base side will be

$$r^* = \frac{2}{\pi}\left(\frac{6E\gamma}{\sigma_m^2(1-2\nu)} + \frac{\delta}{\sqrt{3}}\right).$$

Knowing the value of r^*, it is possible to find the number of fragments N, assuming that the dimensions of the parallelepipeds (fragments) are equal (see Fig. 1).

$$N = D^2/(2r^*)^2,$$

where D is the length of the side of the square within which the number of the fragments is determined.

According to GOST 5727–88, $D = 5 \times 10^{-2}$ m and the minimum number of fragments is 40. Then taking this into account, we can write

$$N = \frac{0.25 \times 10^{-2}}{\left(\frac{6E\gamma}{2\sigma_c/3)^2(1-2\nu)} + \frac{\delta}{\sqrt{3}}\right)^2}\frac{\pi^2}{16}. \tag{9}$$

The minimum necessary degree of tempering (central stresses) is equal to

$$\sigma_u^{min} = \sqrt{\frac{13{,}5E\gamma}{(1-2\nu)\left(\frac{\pi D}{16\sqrt{2{,}5}} - \frac{\delta}{\sqrt{3}}\right)}}$$

Fig. 2 shows the results of the calculations using formula (9) compared to the experimental data [2 – 5]. Note that with

a degree of tempering below 2 pore/cm, significant scattering in the results is exhibited by all authors. At $\Delta \geq 2$ pore/cm, the agreement of the data obtained becomes better but the difference still reaches 150 – 200%. The only exceptions are the results of the experiments carried out on glass 5 mm thick and with $\Delta \approx 2$ pore/cm. For this glass, the data almost coincide, therefore these results are highlighted in Fig. 2 with dark symbols. These experimental points are arranged closely enough to the estimated curve. The relative error of the calculation exceeds 5% in only one case (but does not exceed 10%). In four out of five cases of the comparison between the estimated and the experimental data, the actual level of safety was higher than the predicted level.

Thus, the interrelation between the number of fragments of fractured glass and the degree of its tempering was determined. The equations obtained make it possible to determine the degree of tempering needed to ensure safe fragmentation of tempered glass, to predict the average size of the fragments, and to take into account the physical properties of the glass depending on its composition (modulus of elasticity, Poisson coefficient, density of surface energy).

The dependences obtained maaake it possible to take into proper account of the thickness of the glass in the calculations. (In our opinion, it is especially important since a formula not taking the glass thickness into account cannot be of practical significance). Prediction of the nature of fragmentation of tempered glass of a particular composition and width makes nonintrusive testing (check) of glass safety in fracture possible.

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